Photoevaporation of protoplanetary disks

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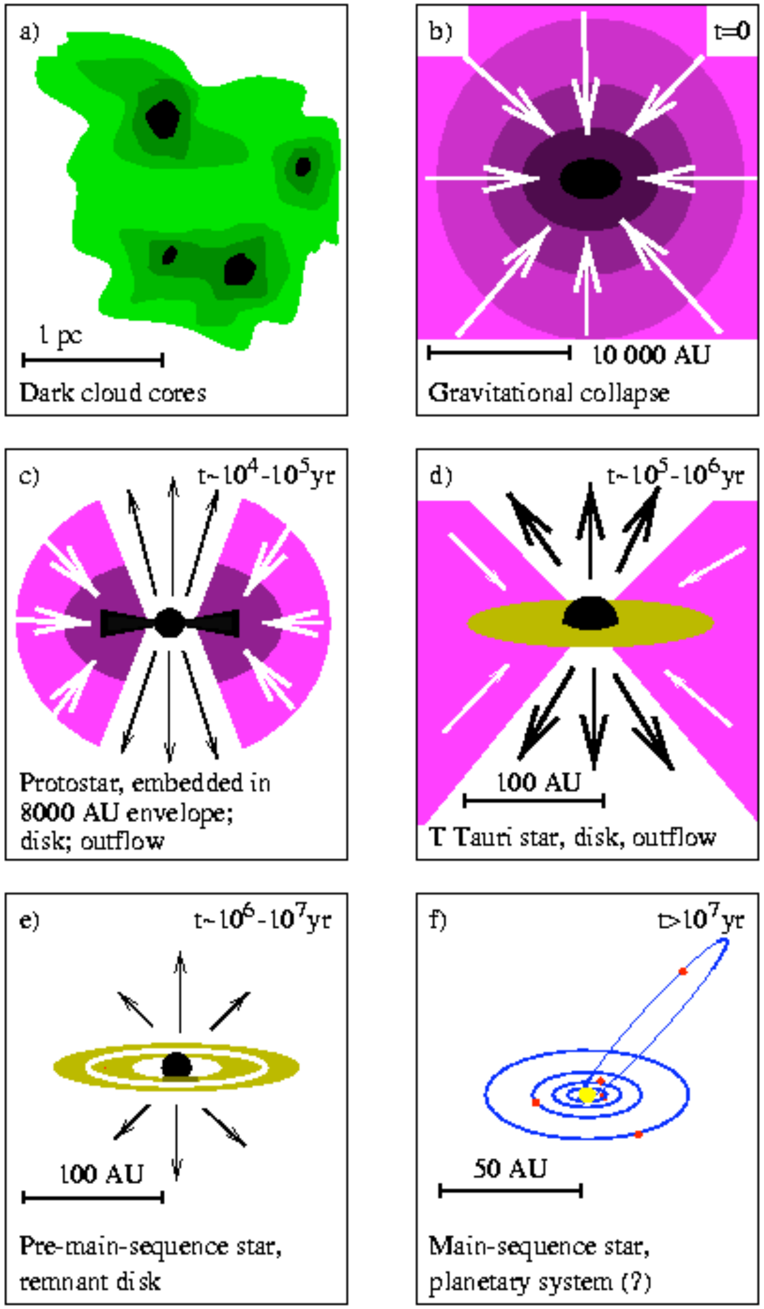


Hogerheijde 1998, after Shu et al. 1987

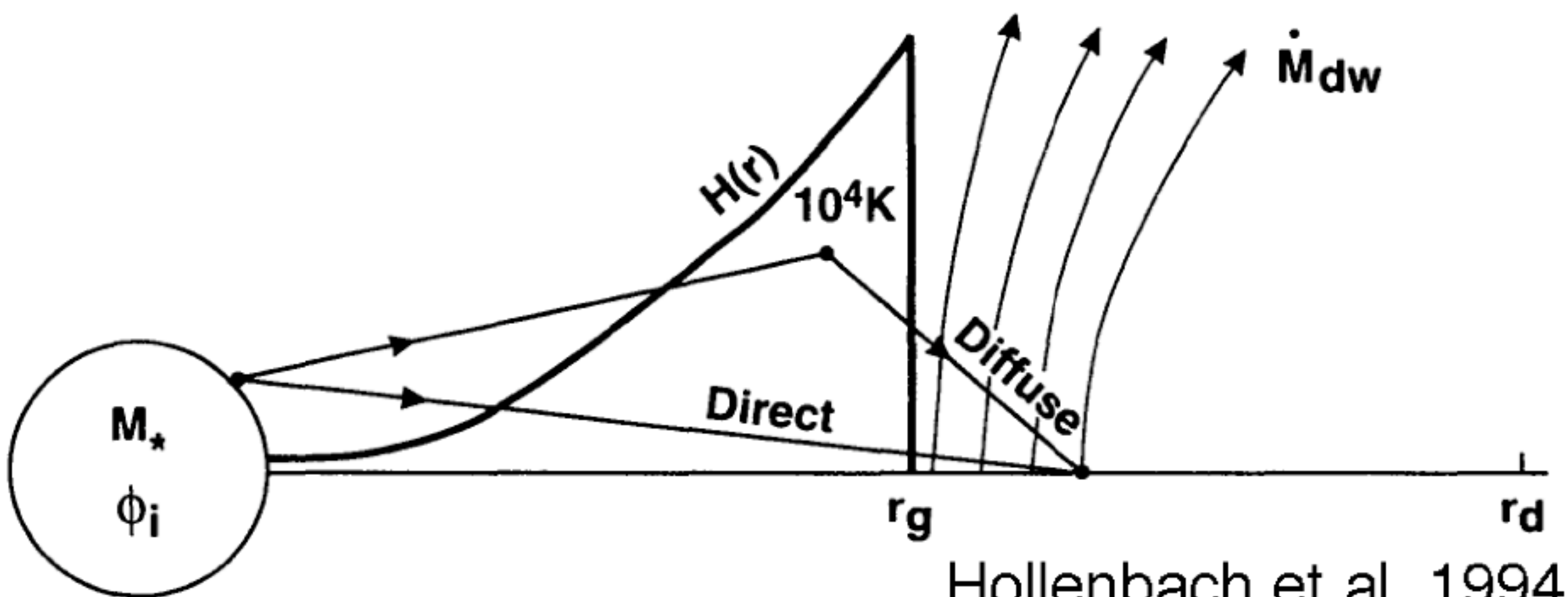
Disk removal affects terrestrial & gas giant planet formation, planet migration

Disk removal mechanisms

- Viscous acrretion
- Photoevaporation driven by central star or external stars, by FUV (Hollenbach & Gorti, #22) or EUV. Photoevaporation by FUV external stars (d~0.1pc): disks shrink to ~15AU in ~10 Myr (Adams et al. astroph/0404383).
- Stellar encounters
- Stellar winds

Hollenbach et al. 2000, PPIV

Photoevaporation by the central star



Hollenbach et al. 1994

EUV photoevaporation (by the central star) + viscous accretion

$$M_* = 1M_\odot$$

$$M_d = 10^{-2}M_*$$

$$\Sigma \propto R^{-1}, T_d \propto R^{-1/2}$$

$$\alpha = 10^{-3}$$

Shakura & Sunyaev 1973, A&A, 24
Pringle 1981, ARA&A, 19
Hartmann et al. 1998, ApJ, 495

$$n_{II}(R_g) = 7.5 \times 10^5 cm^{-3} \left(\frac{\phi_{EUV}}{10^{42} s^{-1}}\right)^{1/2} \left(\frac{R_g}{2.4AU}\right)^{-3/2}$$

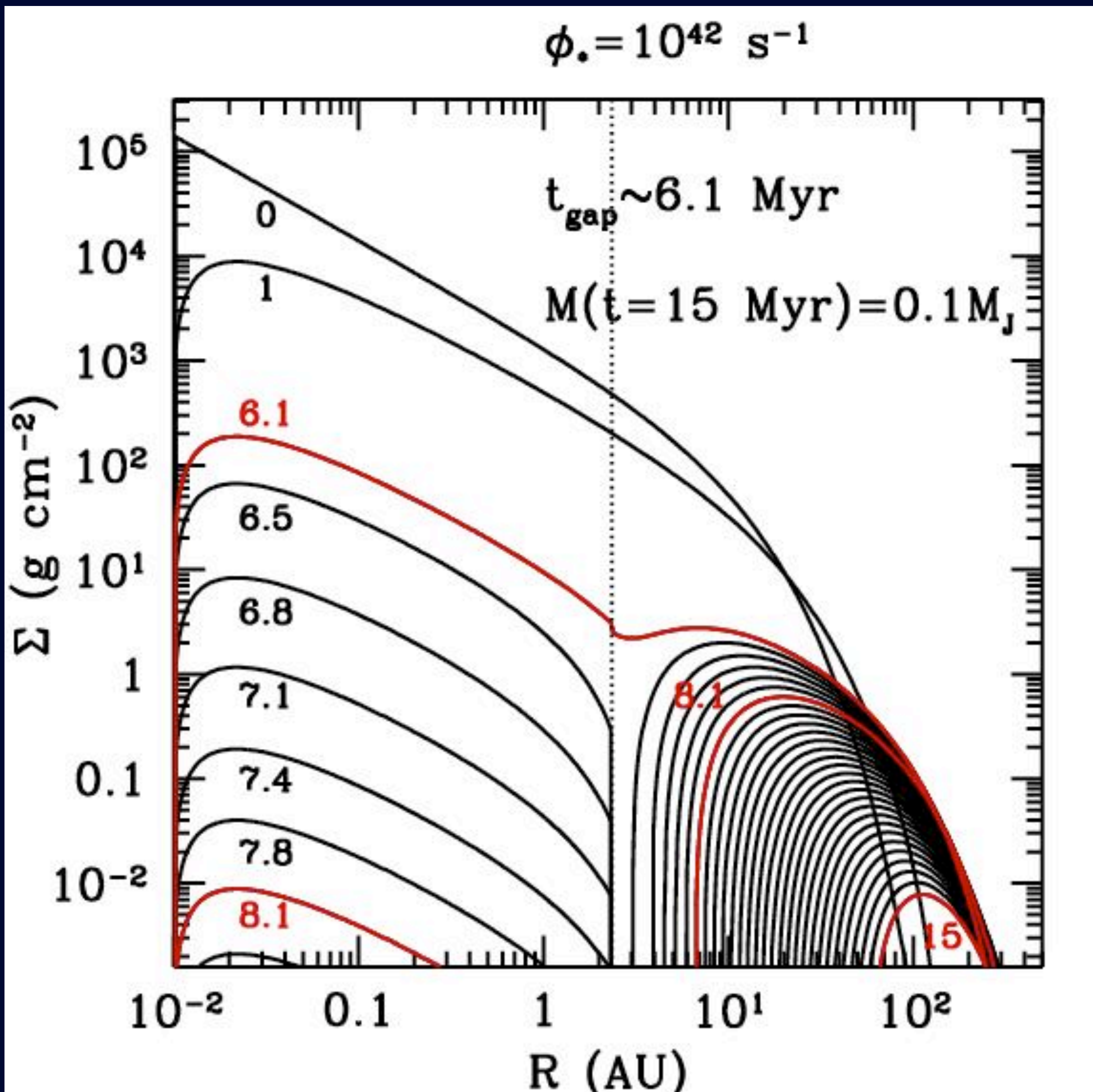
$$n_{II} = n_{II}(R_g) \left(\frac{R}{R_g}\right)^{-5/2}$$

Hollenbach et al. 1994 ApJ 428

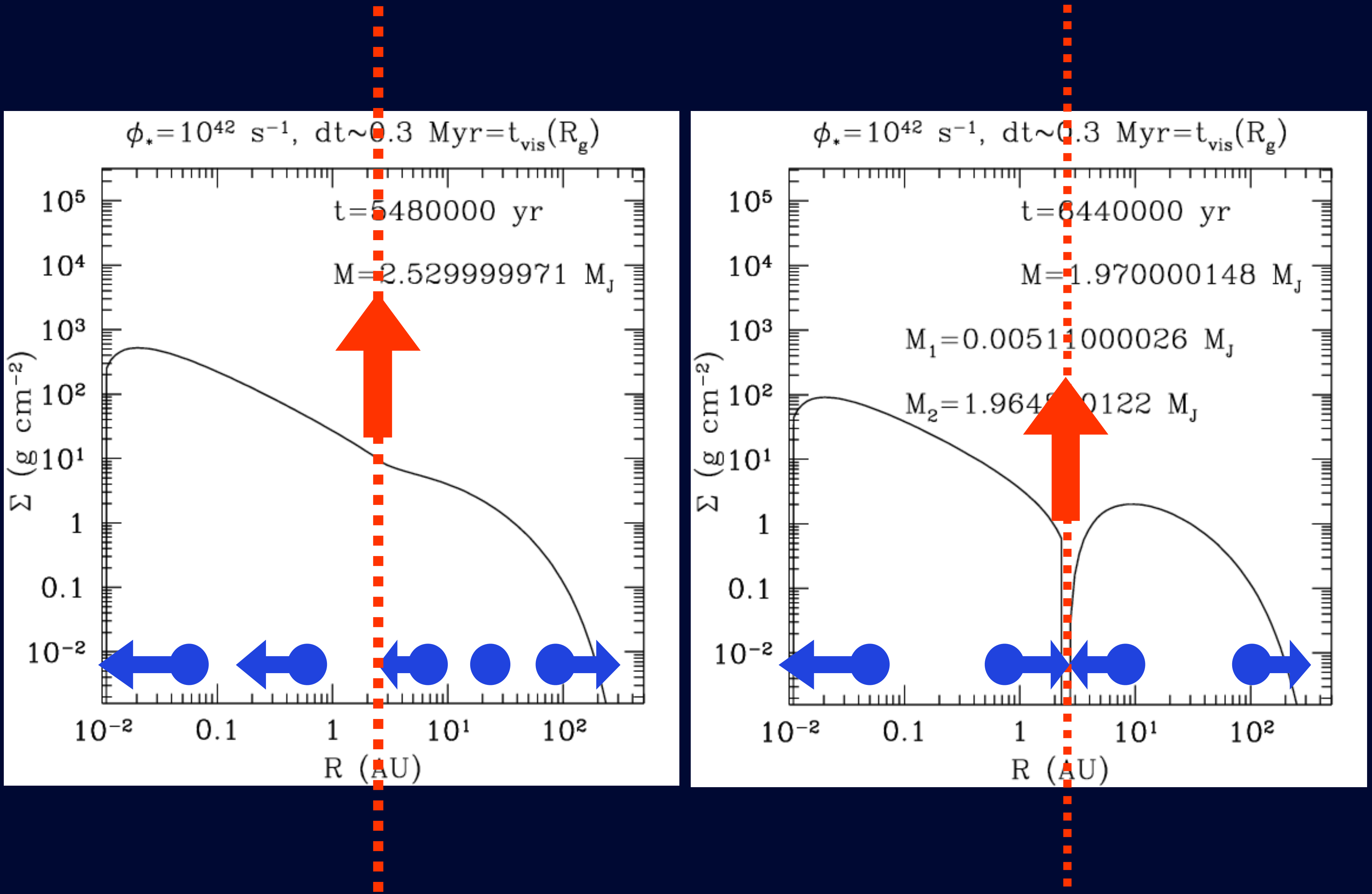
R_g $2.4AU$ Font et al. 2004, ApJ, 607

$$\phi_{EUV} = 10^{42} s^{-1} (\phi_{EUV,\odot} \sim 10^{37} s^{-1})$$

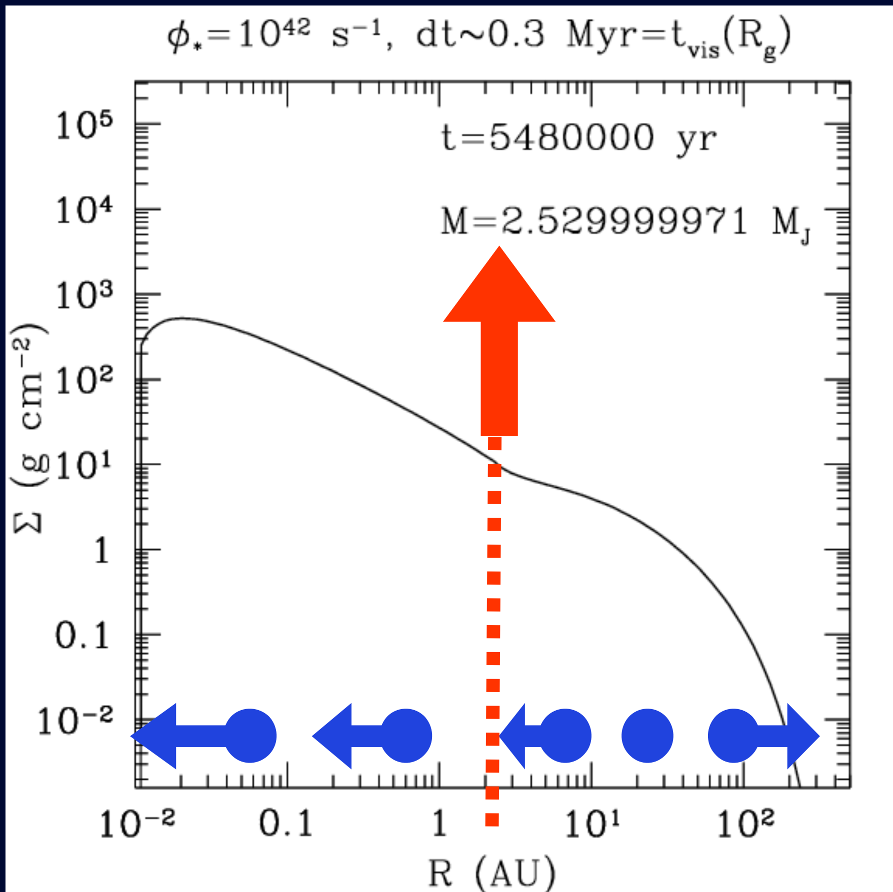
Observations: 1e41-1e44 ?
Alexander et al. poster 2, astroph/0501100

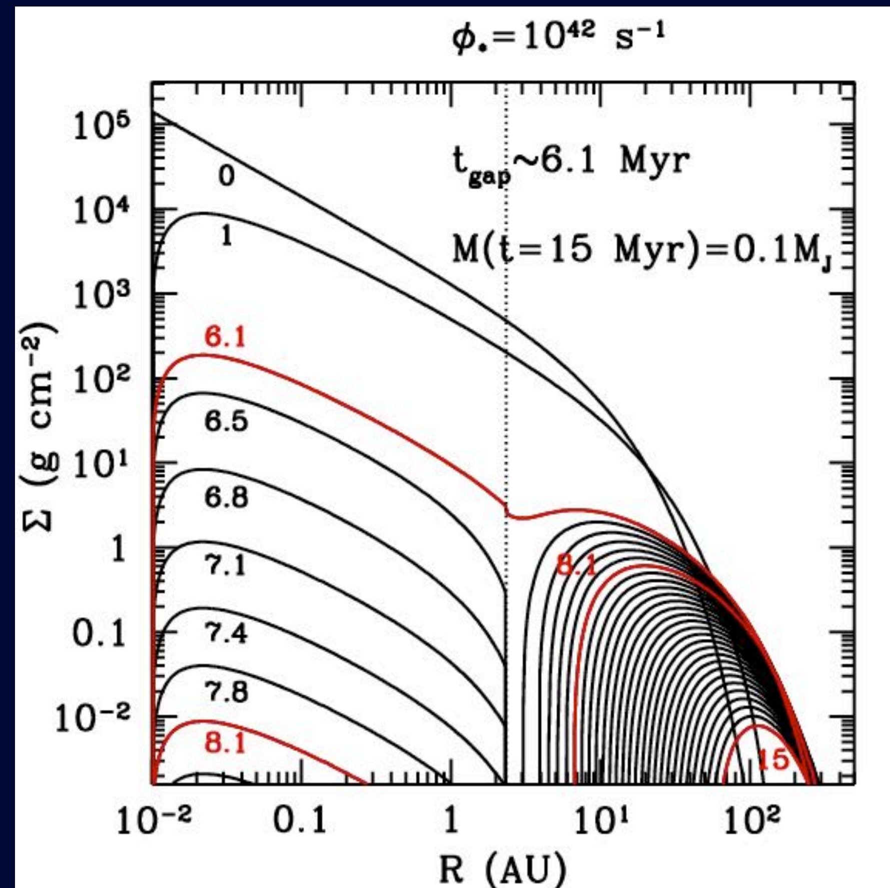


- Consistent with observed inner gas disk lifetimes, and inner (dust) disk lifetime ~10 Myr
- Clarke et al. 2001, MNRAS, 328, 485: inner disk (gas) transition time << (gas) disk lifetime, consistent with small number of (dust) transition objects.
- Gas disks have inner holes of a few AU (Bergin et al. 2004, ApJ, 614; talks by John Carr & Sean Brittain)
- How is the disk inside Rg removed?



φ*=10^42 s^-1, dt~0.3 Myr=t_vis(R_g)
t=5480000 yr
M=2.529999971 M_J
Σ (g cm^-2)
R (AU)
φ*=10^42 s^-1, dt~0.3 Myr=t_vis(R_g)
t=6440000 yr
M=1.970000148 M_J
Σ (g cm^-2)
R (AU)

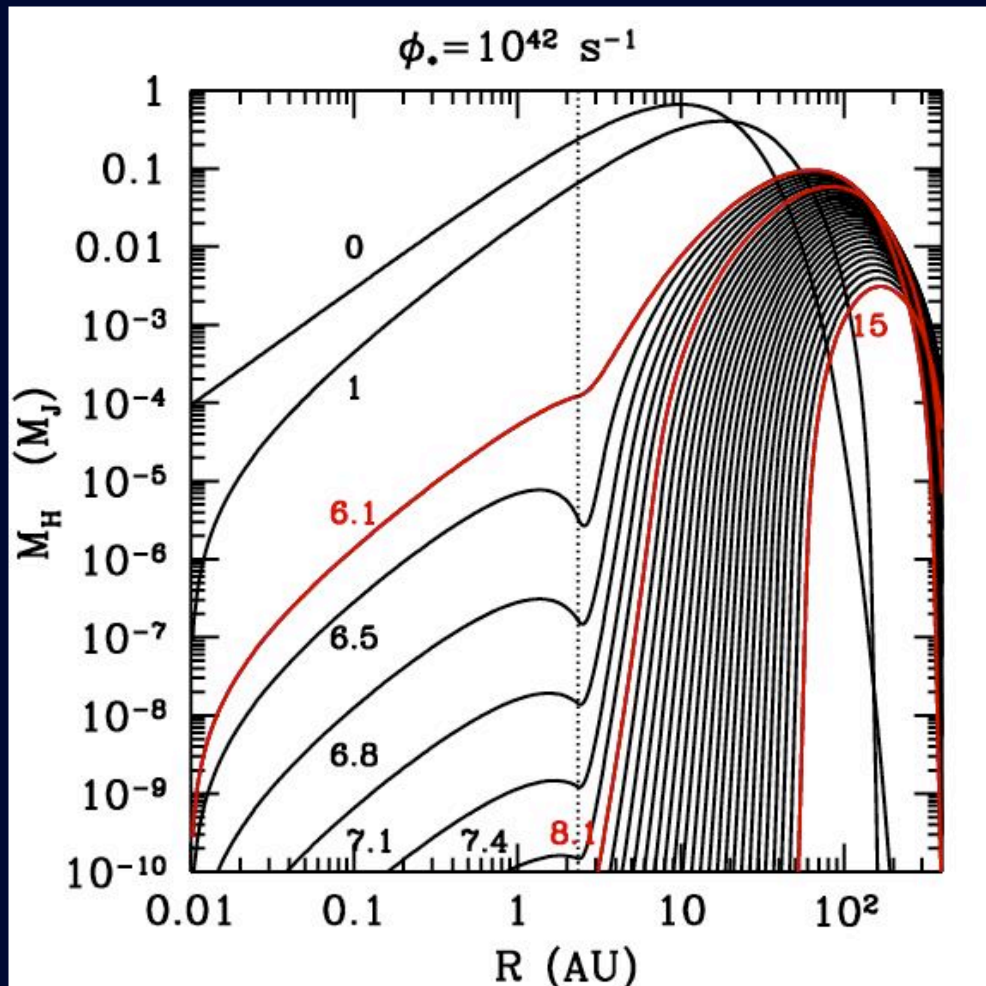




$$\Sigma_{gap} \sim 10 g cm^{-2} \left(\frac{\alpha}{10^{-3}}\right)^{-1} \left(\frac{\phi_\star}{10^{42} s^{-1}}\right)^{1/2} \left(\frac{R_g}{2.4 AU}\right)^{-1}$$

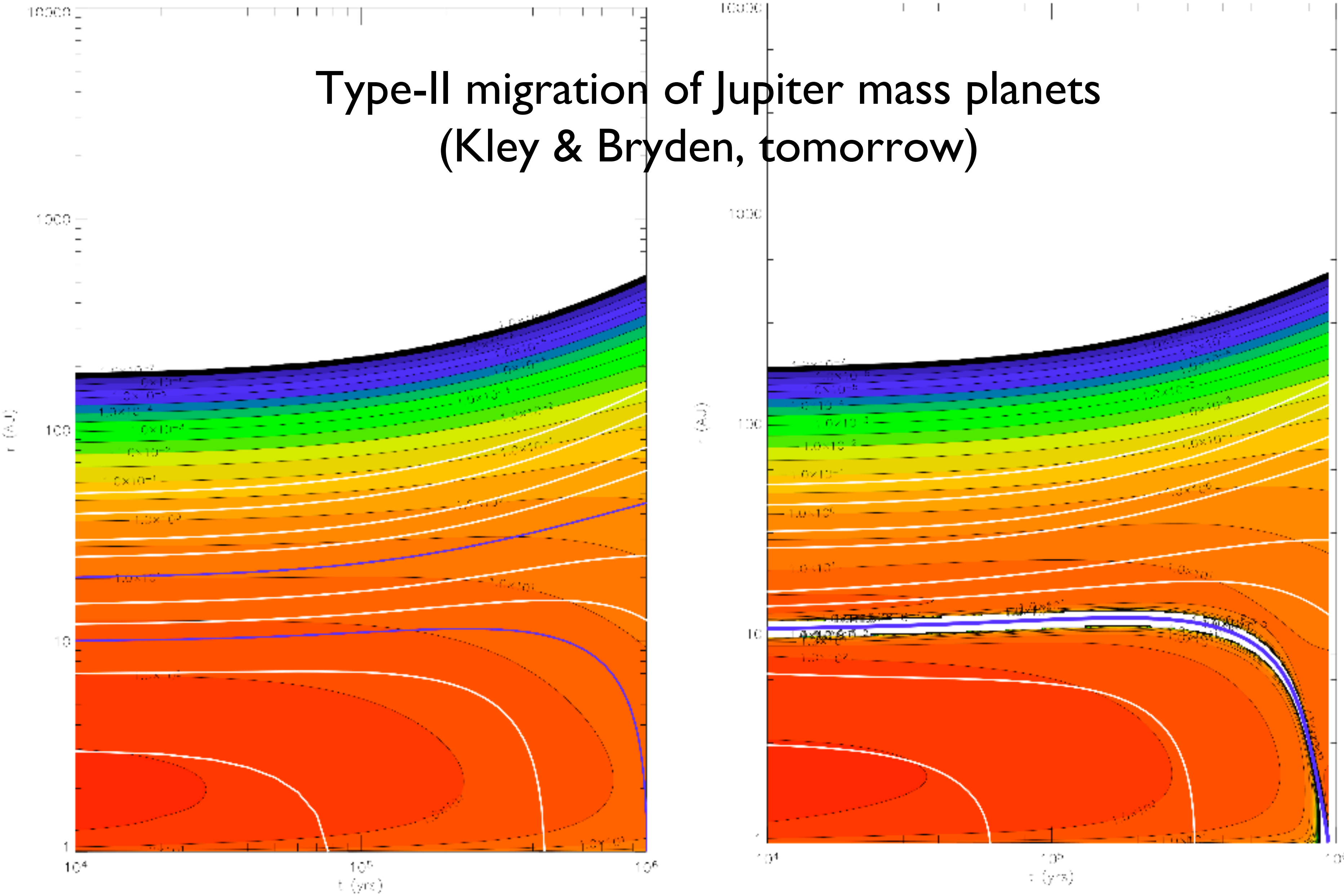
$$t_\nu(R) \sim 3 \times 10^5 yr \left(\frac{\alpha}{10^{-3}}\right)^{-1} \left(\frac{R}{2.4 AU}\right)^{1/2}$$

Planet feeding mass



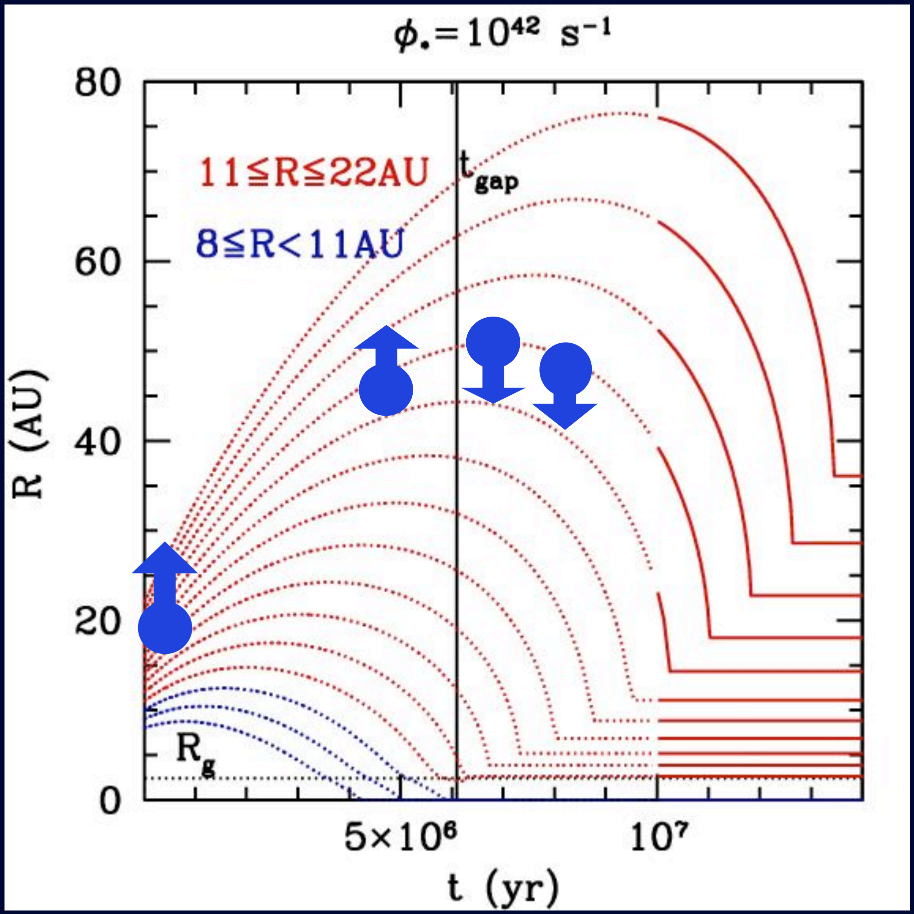
$$m_H(R) = \Sigma 2\pi R 2 R_H = 4\pi R^2 \left(\frac{m_p}{M_*}\right)^{1/3}$$

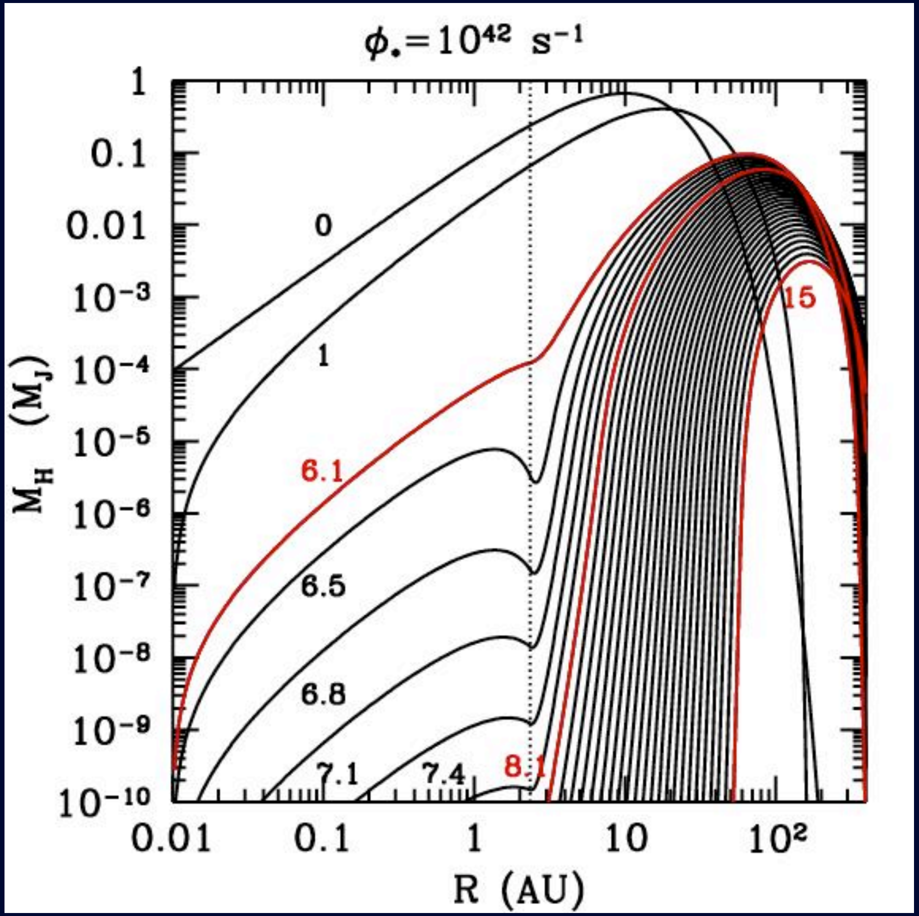
Type-II migration of Jupiter mass planets
(Kley & Bryden, tomorrow)



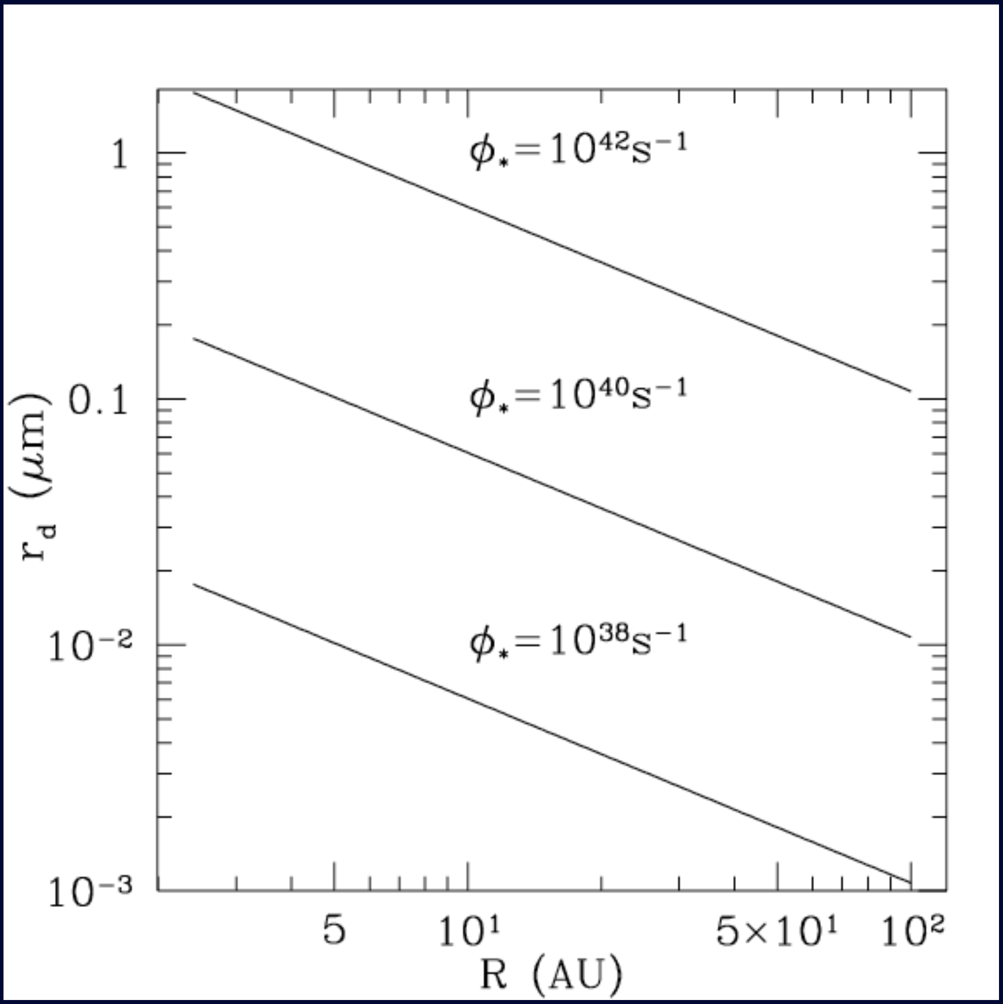
Thommes 2005 astroph/0502427

Disk stream lines





Planetesimal formation



$$r_{dust} < 3\mu m \left(\frac{\phi_{EUV}}{10^{42}s^{-1}}\right)^{1/2}\left(\frac{R}{AU}\right)^{-3/4}$$

- Planetesimal formation by dust sticking (gas: inward migration) or gravitational instability (Goldreich & Ward 1973, ApJ, 183) (gas: turbulence).
- Planetesimal formation by gravitational instability requires a dust to gas ratio increase of x 2-10 (Youding & Shu 2002).
- Strong EUV favors planetesimal formation, but is there enough gas left for GG formation ?
- External photoevaporation + dust growth + vertical sedimentation (Throop & Bally, astroph/0411647): may induce rapid planetesimal formation.

Presence of gas

- Gas giants
- Planet migration is not always inward (Kley, Bryden; Nelson)
- Planetesimals coexisting with protoplanetary cores in a gas speeds up oligarchic growth pahse of formation by core accretion (Rafikov 2004).
- Circularization of orbits, stable planetary systems.

Summary

- Viscous diffusion + photoevaporation = efficient disk removal mechanism.
- Inner disk removal time scale is consistent with observations, corresponds to the viscous diffusion time scale at Rg.
- Gas giants formation by core accretion is not possible if the runaway gas accretion phase starts after ~10 Myr.
- Photoevaporation gap formation, provides a possible halting mechanism for type-II migration at several AU.
- Photoevaporation may stop the inward migration of ~m size objects formed by dust sticking.
- Photoevaporation may induce planetesimal formation by gravitational instability.